CONTACT FATIGUE RESISTANCE OF SINTERED MATERIALS FOLLOWED BY LASER HARDENING

J. Čerňan, D. Rodziňák, K. Semrád, J. Briančin

Abstract

This article deals with the effects of laser hardening on contact fatigue resistance of sintered material. Object tested were sintered materials based on Astaloy CrL powder in two variants (with addition of 0.3% and 0.7% C). Laser hardening was carried out on a TRUMPF TruDisk series 8002 device under conditions resulting from our previous investigations. By suitable combination of operating laser parameters it is possible to obtain on the material surface an increase of temperature into the austenite area which is followed by cooling in terms of the shape and dimensions of the tested samples. This cooling is relatively fast, which gives the opportunity to imitate processes, such as those used by the technology of "sinterhardening". In accordance with CCT diagrams for these steel types, in the affected zone there are developed microstructures similar to classical hardening. Compared to the sintered state, structural changes occurred on the surface at selected laser parameters. Their depths depended on the studied material version and ranged from 440 to 690 μm. The microhardness values of microstructure composed primarily of upper / lower bainite or ferrite ranged from 300 to 600 HV 0.05.

The contact fatigue tests have shown the change in contact fatigue resistance of materials on the laser affected surface as compared to the sintered state. The stress amplitude to the lifetime value of $50 \cdot 10^6$ cycles has increased about 25% in both material variants. The results showed otherwise some beneficial effects, but it is possible to state that this increase is not that significant compared with other methods of surface hardening. However, this result is valid only for bainitic microstructures. Harder martensitic microstructures can be achieved on the material surface by laser hardening. Their use should be the subject of our further investigation.

Keywords: Cr-Mo sintered steels, contact fatigue, laser surface modification, microscopic analysis

INTRODUCTION

Surface hardening of compact materials or finished machine parts is an ancient technology known in several variants. It involves either reinforcing the mechanical, thermal, chemical - thermal characteristics or hardening by coating. In any case, such treatment is used when the material is stressed by a specific load. Surface hardening is one of the possibilities of affecting the surface properties mainly of ferrous materials among

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other things. During this process, an improvement of mechanical properties of the affected layers occurs which has a positive effect e.g. on fatigue properties including resistance to contact fatigue as well.

Surface hardening also has its place in the area of sintered materials. In previous works, we examined its effect on the Astaloy CrL/CrM sintered material.

It was for example cementation [1], classical as well as plasma nitriding [2-3], mechanical reinforcement by shot peening [4], coating [5] as well as the influence of laser hardening onchanges in the structure [6]. Most of these aspects have also been investigated by other authors on similar types of sintered materials. It seems that the methods valid for compact materials are also suitable for sintered materials [7-13].

This article deals with the influence of laser hardening on contact fatigue resistance. In conventional materials, the technology has already been used successfully for some time. Its use is subject to the following criteria:

- the required surface layer has to be heated above the austenitising temperature and held at this temperature during austenite homogenization,
- the surface area subjected to heat treatment must be in good contact with an adequate volume of base material due to the intense heat transfer and the effect of self-cooling.

Key process parameters are: laser power, beam width and speed of its movement, laser beam mode - the shape and energy distribution, absorption of laser radiation by the material surface as well as properties of the material and its microstructure. And as it has been said, of no less importance is the total volume of the material, which determines the rate of cooling and the resulting type of microstructure. As it can be seen, there are lots of factors which affect the overall result. Changing only one of them can significantly affect the overall result.

EXPERIMENTAL

The samples were prepared from prealloyed Astaloy CrL (Fe-1.5% Cr-0.2% Mo) powder (Höganäs AB, Sweden). Two sets of samples were prepared by adding graphite powder in an amount of 0.3 / 0.7%. After the addition of 0.6% HWC type lubricant, the samples were compacted at 600 MPa in the form of cylindrical specimens, dimension ф 30 x 5 mm. Then the samples were sintered in a controlled atmosphere (90% N_2 +10% H_2) at 1120°C for 60 min. Before sintering, the sintering atmosphere was frozen - dew point of -57°C. The samples were placed into a retort with a mixture of Al_2O_3 with the addition of 1% C to avoid possible undesirable oxidation and decarburization of sample surfaces. After sintering, the samples were cooled outside the furnace in an inert atmosphere. Subsequently, they were machined to an outer diameter of ф 28 mm with an internal hole of ф 10 mm and finally ground to achieve flatness on both circular areas. The density of samples was 7.01/6.98 $g{\cdot}cm^{-3}$. The special shape of the samples was made due to the fact that these samples were also used for contact fatigue testing after laser hardening. All samples were subjected to laser hardening by a diode-pumped solid-state laser system TRUMPF TRUDISK series 8002 under the following conditions. The samples were sprayed with a matt black paint (paint hot Plasti-Kote industrial) resistant to higher temperatures to increase the absorption. The carrying beam was 2 kW, 4 mm diameter fibre. The progressive rate of the laser beam was 35 mm/s set only experimentally, on the basis of the experience of the device operator. The process was controlled by a constant beam power. Hardening was done in a protective argon gas streaming at 15 l / min. Sample hardening was carried out in one way at a track width of 4 mm. The second track of the same width overlapped the first track by the value of about 1 mm. The entire surface of the sample was covered in this way. Its principle is shown in Fig.1a, b, with the overall result shown in Fig.3a, b.

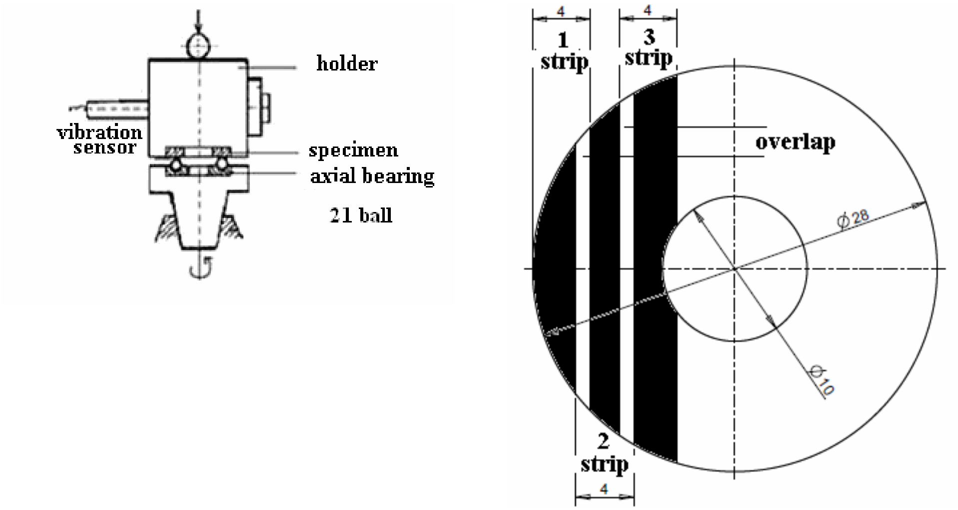


Fig.1. a) Principle of laser hardening and b) hardened tracks on the test sample.

Two sets of samples having undergone the preparation as described above were subsequently subjected to contact fatigue tests (using the pin-on-disc system) applying the AXMAT type device – Fig.2a, b, operating at 500 rpm.

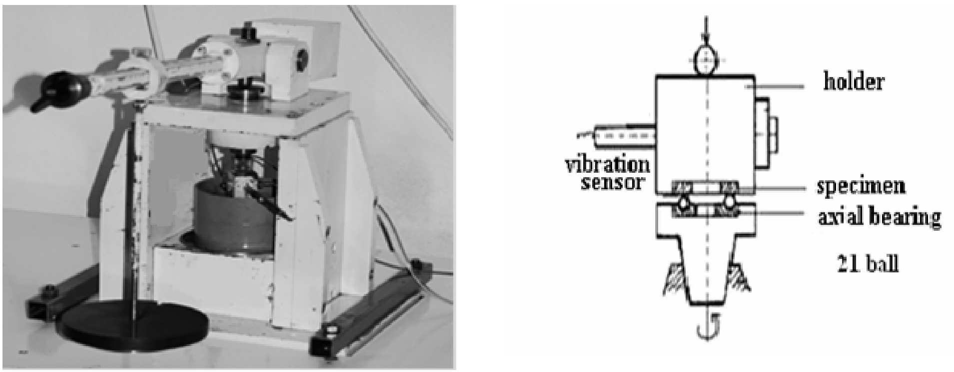
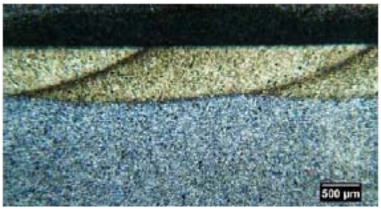


Fig.2a, b. Appearance and the principle of the Axmat testing device.

The samples replaced the upper part of the axial bearing, with 21 balls of 3.175 mm in size, made of bearing steel, rolling on its surface. The balls were located in the lower part of the axial bearing and lubricated with MOGUL SAE 80 transmission oil, circulated and constantly filtered during testing. The contact fatigue test was evaluated by a classical Wöhler curve as well as the method of Weibull life [14] (for this evaluation 20 samples for each material group were used). After tests, the samples were subjected to metallographic – microscopic analysis, using both optical and SEM microscopes. Hardness values were determined by conventional Vickers HV 0.05 tests.

RESULTS AND DISCUSSION

Metallographic analysis of the samples after laser hardening under the selected conditions has shown the influence of the surface layer in a depth, which is visible from Figs. 3a, b. Figure 3a shows the effect of the material in a direction perpendicular to the movement of the laser beam. There is also visible the translation of individual tracks at the parallel movement of the beam. Figure 3b shows the same effect in the longitudinal direction forming a uniform layer.



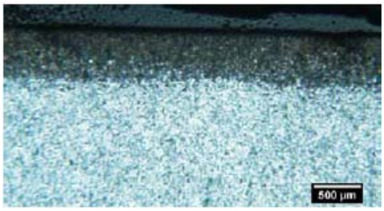


Fig.3a, b. Appearance of the affected area on the AstCrL + 0.7% C material in the direction perpendicular and parallel to the movement of the laser beam.

The depth of affected area for both investigated materials can be read from the diagram in Fig.4. The diagram is based on the results that have been published in [6] and the values for the speed of beam 35 mm /s have also been entered into the diagram. Thus, it can be concluded that it is possible to qualitatively assess the impact of the speed of movement of the beam on the structural changes and the resulting changes of mechanical properties.

Materials with higher carbon content have obviously affected the surface more in depth. Measuring the microhardness along the cross section of the samples revealed the facts well visible in Fig.5. Again, logically, the values for materials with higher carbon content are higher. The hardness curve shows that in the material with 0.7% C content the hardness on the cross section changes minimally and a decrease occurs somewhere at the depth of approximately 500 µm. The decrease of hardness to the value typical for sintered material, however, occurs at about 590 µm. The marked points of the depth values correspond well with those obtained from microscopic observation. This is valid of course for the materials with carbon content of 0.3% C, with the difference that in this case the decrease of microhardness is continuous from the surface down to the value of the sintered state. The gradual decrease in hardness of the sample with 0.3% C versus 0.7% C is influenced by lower through-hardening of material with 0.3% C.

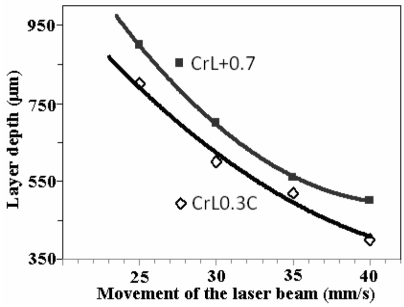


Fig.4. Depth influence of the cross-section.

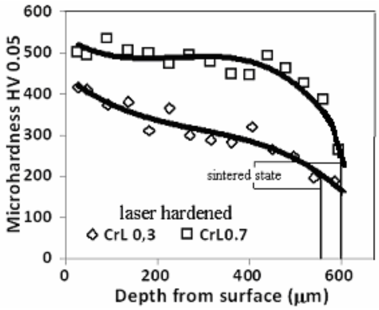


Fig.5. Microhardness along the cross section by laser beam movement speed 35mm/s.

Microhardness values correspond to structures formed after laser hardening - Figs.6, 7. Heating the material into austenite area and its subsequent spontaneous cooling correspond logically to CCT diagrams that were constructed for this type of AstCrL material [15-16].

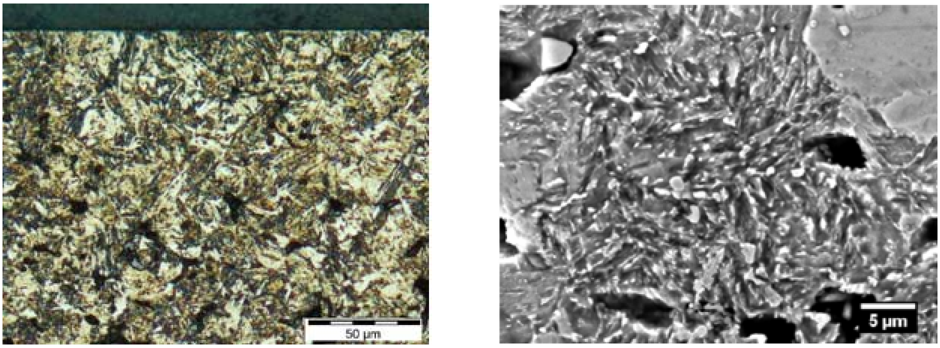


Fig.6. Microstructure of AstCrL + 0.3% C material after hardening (in the affected area): a -LOM, b - SEM.

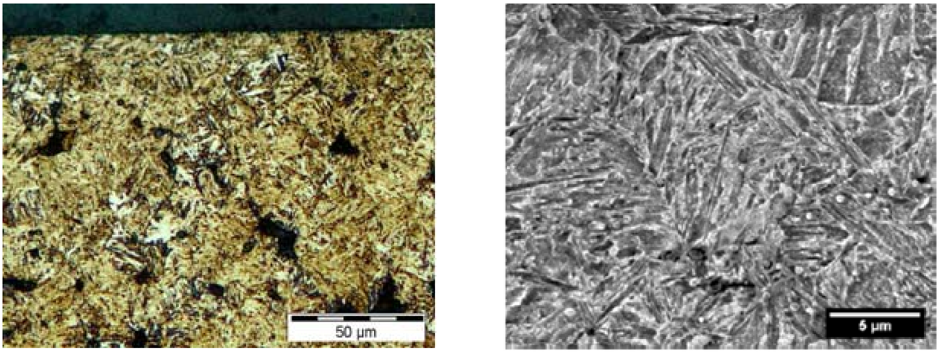


Fig.7. Microstructure of AstCrL + 0.7% C material after hardening 5 (in the affected area): a – LOM, b – SEM.

From the diagrams it is evident that for this PM material type the temperature of austenite transformation drops with carbon content. In practice it was confirmed by microscopic analysis of the microstructures created by laser treatment. Sintered AstCrL material with different carbon content has a ferritic - pearlitic microstructure with the pearlite amount equalling the carbon content. After laser hardening in accordance with the cooling rate, the material in each case has bainitic microstructure with the corresponding ferrite proportion – Fig.6a, 7a. In the case of material AstCrL + 0.7% C predominantly lower bainite was formed. This fact is confirmed by microhardness values in the range of 450-500 HV 0.05. In AstCrL +0.3% C material, mostly upper bainite was formed with the corresponding hardness ~ 400 HV 0.05. The difference between the upper and lower bainite is evident from the comparison of Figs.6b-7b. The lower hardness values and their permanent decrease for specimens with 0.3% C content are already due to the increasing proportion of ferrite in the microstructure.

Contact fatigue tests demonstrated the effect of laser hardening on the resistance of the AstCrL material. For comparison the curves for sintered state are shown. As shown in Fig.8a, b for material with 0.3% C the fatigue strength has increased from 750 MPa to 950 MPa, an increase of 26%. In material with 0.7% C it is an increase from 1000 MPa to 1250 MPa, which is 25%.

For further considerations we assume that the values for construction of the Wöhler curve are values with 50% probability of pitting creation. In order to verify these values, we built a Weibull curve probability of damage to the test at a constant stress of 1000 MPa using 20 samples for each material. The results (in millions of cycles) are shown in Table 1, as well as the constructed Weibull curve in Fig.9. As seen from Table 1, the arithmetical value of life for the material AstCrL + 0.3% C was $47 \cdot 10^6$ cycles and for material AstCrL + 0.7% C was $69.5 \cdot 10^6$ cycles.

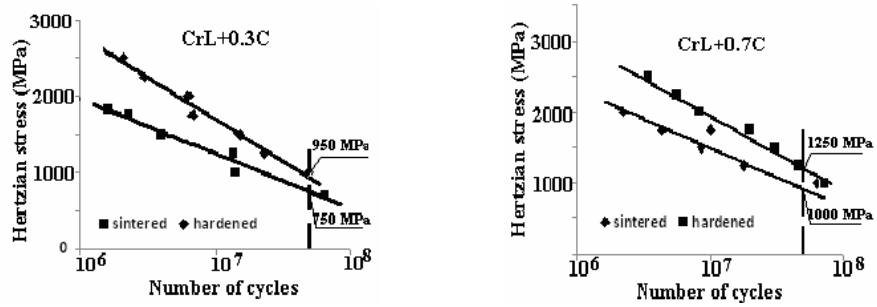


Fig.8a, b. Contact fatigue curves of sintered and laser hardened AstCrL samples.

Tab.1. The arithmetical average values of lifetime in milion cycles from 20 specimens for AstCrL material with 0.3% C and 0.7% C.

Mat.	1	2	3	4	5	6	7	8	9	10	Average value
AstCrL+0.3C	24	26	29	37	37	38	39	39.5	41	48	47
	50	50	50	51	51	54	60	69	71	75	
AstCrL+0.7C	25	27	30	38	43	46	52	59	60	62	69.5
	68	70	73	75	90	100	111	112	123	126	

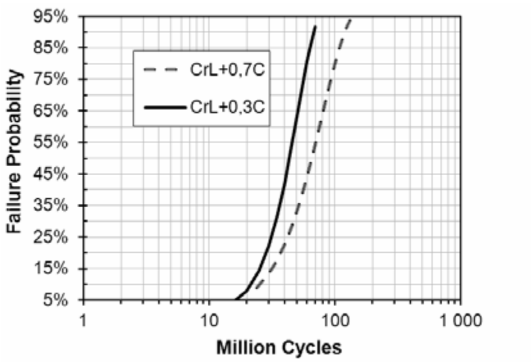


Fig.9. Weibull distribution for AstCrL material.

The graph confirms the fact we have concluded based on the previous results - material with a higher carbon has a longer lifetime at the same conditions. And there is also another coincidence. Considering the values of the Wöhler curves at an approximately 50% probability region, the Weibull distribution obtained also confirms the value of life i.e. $46{\cdot}10^6$ and $69.5{\cdot}10^6$ cycles at 50% probability of failure (see the label on the chart in Fig.9). Metallographic - microscopic observation showed the behaviour of the investigated materials during contact load. Contact fatigue causes formation of pitting on the surface, which are factors limiting life. A classic example of such pitting is shown in Fig.10, which makes evident the spalling mode failure mechanism of surface layer. This fact is also documented by Fig.11, confirming the formation of cracks parallel to the surface in the Hertzian stress peaks. These images were taken from the sample loaded with 1000 MPa stress level with lifetime at about $50{\cdot}10^6$ cycles. The calculated maximum depth of Hertzian stress under load of 1000 MPa is 27 µm. As it can be seen, cracks were developed in this area.

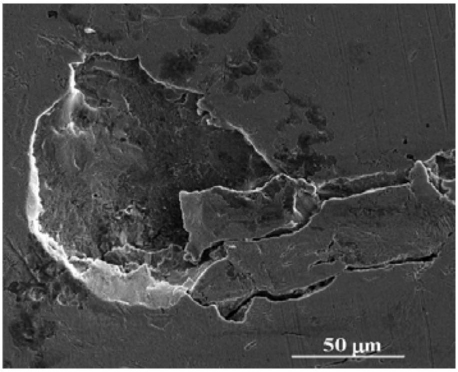


Fig.10. Appearance of pitting.

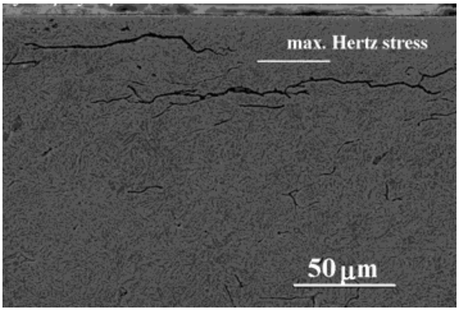


Fig.11. Subsurface cracks.

CONCLUSIONS

The effect of laser hardening on the PM material of Astaloy CrL type with two levels of carbon pointed out both the change in the surface structure and the resistance of this layer to contact fatigue. It is therefore possible to state:

1. Laser hardening is a method of heat treatment which corresponds to surface hardening. It enables one to achieve the microstructures on the material surfaces that are obtained in PM materials through heat treatment, referred to as sinterhardening.
2. The type of microstructure depended on the selected device parameters. In our case, the microstructure was formed mostly of upper or lower bainite (+ ferrite) depending on the carbon content.
3. Change in the microstructure results in an increased surface hardness, which in material with 0.3% C increased from 175 in the sintered state to the value of 300-420 HV0.05 depending on the depth influence, and in material with 0.7% C the hardness values increased from 225 to about 500 HV0.05.
4. Depth of influenced area decreased with the speed of movement of the laser beam and increased with carbon content.
5. Resistance to contact fatigue for the value of $50{\cdot}10^6$ cycles, of such a hardened surface layer for both material variants, increased by 25%.

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REFERENCES

[1] Rodziňák, D., Zahradníček, V., Zahradníček, R., Čajková, A. In: Jubilee 10th International Symposium „Intertribo 2009“. October 2009. The High Tatras, Slovak Republic (in Slovak)
[2] Rodziňák, D., Zahradníček, R., Hvizdoš, P., Jakubéczyová, D.: Acta Metallurgica Slovaca, vol. 16, 2010, no. 1, p. 12
[3] Rodziňák, D., Čerňan J., Semrád, K., Zahradníček, R. In: Poruchy valivých ložísk / Failures of rolling bearings : Internationale Conference. October 2010. Bratislava : Congres management, 2010, p. 71
[4] Rodziňák, D., Čerňan J., Semrád, K., Zahradníček, R.: Vplyv povrchového spevnenia na kontaktnú únavu spekaných materiálov, In: Poruchy valivých ložísk / Failures of rolling bearings : Internationale Conference, October 2010, p.71-74, Bratislava, Slovak Republic. Bratislava : Congres management, 2010, ISBN 978-80-89275-24-3
[5] Čerňan, J., Rodziňák, D., Hvizdoš, P.: Contact fatigue of TiCN coated sintered steels. Metallic Materials, in press
[6] Rodziňák, D., Čerňan, J., Semrád, K., Zahradníček, R.: Acta Metallurgica Slovaca, vol. 19, 2013, no. 4, p. 202
[7] Stewart, S., Ahmed, R.: Wear, vol. 253, 2002, p. 1132
[8] Kanno, K., Takeda, Y., Bergmark, A., Alzati, L., Lundqist, B., Ueda, Y., Kanda, K., Zandonati, A. In: International Conference PM 2004, Vienna, Austria. Vol. 3. London : EPMA, 2004, p. 179
[9] Lawcock, R. In: Proceedings of the International Conference on Powder Metallurgy and Particulate Materials, Montreal, Canada. Part 10. Princeton, NY : MPIF, 2005, p. 121
[10] Johansson, P., Bengtsson, S., Dizdar, S. In: PM²TEC 2002. World Congress on Powder Metallurgy and Particulate Materials. Orlando, USA, June 2002, http://www.hoganas.com
[11] Warzel, R., Milligan, D., Enstrom, U. In: PowderMet 2007. Denver, USA, 2007, p. 1
[12] Bengtsson, S., Marcu, T., Klekovkin, A. In: PM 2008. Washington, USA, 2008, p. 1
[13] Fillari, G., Marucci, M. In: Advances in powder metallurgy and particulate materials. MPIF, 2005, p. 6
[14] Semrád, K. Zahradníček, R. In: International conference on military technologies 2011. Brno : University of Defence, 2011, p. 551
[15] Berg, S., Maroli, B. In: PM2TEC 2002. World Congress on Powder Metallurgy and Particulate Materials. Orlando, USA, 2002, p. 1
[16] Lewenhagen, J.: Materials Science Forum, vol. 416-418, 2003, p. 241